Rockfall Hazard Condition at Makena State Park
Maui, Hawaii

Prepared for

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October 30, 2006

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Significant rockfalls occurred along the rock cliffs at Makena State Park after the October 15 earthquakes, with at least ten easily recognizable rockfall sources, eight of them at Black Sand Beach (Photo 1), two at Big Beach (Photo 2), and none at Small Beach.

Sources of Rockfalls

All rockfall sources are parts of Pu'u Ola'i volcanic cinder cone at Makena State Park. Photo 3 shows close view of rockfall sources close to S1 as shown in Photo 1. Photo 4 shows close view of rockfall sources S2, S3, and S4 together with unstable loose cinder blocks perched on steep slope. Photo 5 shows close view of rockfall source S5 and rockfall debris piles on the beach. Wave erosion has removed most of the debris (Photo 6). Photo 7 shows close view of rockfall sources S6 and S7. Photo 8 and Photo 9 show close views of rockfall sources S8 and S9 respectively as shown in Photo 2 at Big Beach.

Reaches of Rockfalls

At Black Sand Beach, the narrow beach could easily be covered by rockfall debris of small loose cinders (Photo 6) and large cinder blocks (Photo 10). There is no safe zone on the narrow beach in case of rockfalls at Black Sand Beach. Some large cinder blocks could even go over 40 feet into the water (Photo 10).

At Big Beach, only portions of the wide beach could be reached by rockfall debris of small loose cinders (Photo 8) and large cinder blocks (Photo 11). Most parts of Big Beach are safe in case of rockfalls (Photo 2).

Current Rockfall Hazards at Black Sand Beach

A condition of significant rockfall hazards to beach users currently exist at Black Sand Beach after the Oct. 15 earthquakes. There are four types of rockfall hazards at Black Sand Beach:

1) Significant loose cinder debris (Photo 3) and loose cinder blocks or boulders (Photo 4, Photo 7 and Photo 12) currently exist on the steep slope with slope angle close to the angle of repose (the steepest angle at which loose fragments will stand without sliding or rolling downhill).

2) Hard cinder layers on top of soft cinder layers have significant overhangs and tension fractures due to the differential erosion of the soft layers (Photo 13 and Photo 14).

3) Relatively large sizes of slope failures may occur along fault zones (Photo 15) and large tension fractures (Photo 5).

4) Falling of egg-sized (or larger) cinders onto the beach will be pervasive (Photo 17) as most cinder layers at Black Sand Beach are loose with poor cementation (Photo 16).

Current Rockfall Hazards at Big Beach

Most of the cinder layers at Big Beach are quite different from those at Black Sand Beach. Compared to the steep dipping angles (close to 40 degrees, the angle of repose) of cinder layers at Black Sand Beach (Photo 3, Photo 4, Photo 5, and Photo 7), the dipping angles of most cinder layers at Big Beach are much gentler (Photo 2, Photo 8, and Photo 11) with only a thin and steep-dipping surface veneer layer (Photo 2 and Photo 9). In addition, the gentle-dipping cinder layers at Big Beach are very hard with strong welding between cinders (Photo 18). The gentle-dipping cinder layers at Big Beach probably are part of an old cinder cone formed directly by the deposition of hot cinders (good welding and no sliding after deposition) while the steep-dipping loose cinder layers at Black Sand Beach are part of a new cone formed by the deposition of relatively cold cinders and further sliding after deposition to take the angle of repose (Photo 19).

Rockfall hazards at Big Beach include a few loose boulders, the weak veneer layer (Photo 9), and the fractured and overhang hard cinder layers (Photo 8, Photo 18 and Photo 20). The rate to produce new rockfalls in the hard cinder layers at Big Beach is much slower than that in the loose cinder layers at Black Sand Beach.

Rockfall hazards for Small Beach are not observed during the very limited field investigation but could exit if loose boulders are to be found on the slope above the Small Beach.

Recommended Mitigation Methods for Big Beach

For Big Beach, scaling and optional limited demolition and bolting are recommended. Scaling will remove the loose boulders and hazardous loose debris (Photo 9) and well fractured rocks (Photo 8). Demolition may be used to remove hazardous overhangs if they cannot be removed by scaling (Photo 18). Rock bolting may be used to stabilize large pieces of the hard cinder layers (Photo 20) if their rates of settlement increase with potential for toppling failures. During construction, only small portions of Big Beach need to be closed. The cost of scaling with optional limited demolition and bolting is approximately $100,000.

Draped or pinned meshes covering the whole slope or rockfall impact fences installed at slope bottom are not recommended for Big Beach due to their high costs and adverse aesthetic impacts. Rockfall catchment ditch installed at the slope bottom is not recommended due to its adverse impact on the beach park. Doing nothing is not recommended due to the high usage of Big Beach and the observed existing rockfall hazards.

Recommended Mitigation Methods for Black Sand Beach

For Black Sand Beach, the first three types of rockfall hazards can be similarly addressed by scaling and optional demolition and bolting. The fourth type of rockfall hazards, namely the pervasive and constant falling of egg-sized cinders from loose cinder layers will be difficult to secure. The normal method of shortcreting or pinning a mesh system (with a fine layer and deep anchors) for the whole slope is not recommended due to aesthetic and cost considerations.

We recommend either closing a portion of the Black Sand Beach directly below the mountain to eliminate rockfall hazards or performing periodic scaling to significantly reduce rockfall hazards to within tolerable level. Further data like usage of Black Sand Beach are needed in order to make our final recommendation.

Periodic scaling can significantly reduce rockfall hazards at Black Sand Beach. Scaling will remove the loose boulders and hazardous debris (Photo 3, Photo 4, Photo 7, and Photo 12) and the well fractured blocks in the hard cinder layers (Photo 4). Rock bolting may be used to stabilize large pieces of the hard cinder layers if such pieces are encountered. Scaling of the loose cinder layers should remove overhangs (Photo 17), fractured large blocks (Photo 5), and unstable cinders on slope faces steeper than the angle of repose. The approximate cost of first round of scaling is about $200,000, with much lower cost for later rounds at about very five years.

Doing nothing is not recommended as the calculated risk level associated with rockfalls at Black Sand Beach is likely significantly over tolerable levels depending on actual usage data. For loss of life, the risk level can be calculated from:

$$R_{(DI)} = P_{(H)} \times P_{(S:H)} \times P_{(T:S)} \times V_{(D:T)}$$

Where $R_{(DI)}$ is the risk (annual probability of loss of life (death)); $P_{(H)}$ is the annual probability of the hazardous events (the landslides or rockfalls); $P_{(S:H)}$ is the probability of spatial impact by the hazard (e.g. probability of landslides impacting structures or locations taking into account travel distance); $P_{(T:S)}$ is the temporal probability (e.g. probability of the location being occupied); $V_{(D:T)}$ is the vulnerability (probability of loss of life of individuals given the impacts).

For existing slopes, the suggested tolerable risk for loss of life is 10^{-4} for persons most at risk and 10^{-5} for average persons; for new slopes, the suggested tolerable risk for loss of life is 10^{-5} for persons most at risk and 10^{-6} for average persons (AGS, 2000).

For a first order estimation, let us assume there are 0.2 relatively large size rockfall and 20 egg-sized cinder rockfalls per year along the 500-foot stretch of shoreline at Black Sand Beach. For the large size rockfall, we have: $P_{(H)} = 0.2$ (one rockfall every 5 years along the entire 500 feet long rock cliff), $P_{(S:H)} = 15/500*100\%$ (each rockfall only impacts 15 feet of the 500 ft area and there is 100% chance for a rockfall to reach the beach), $P_{(T:S)} = 3 * 2 /24$ (there are 3 persons for 2 hours each day on the beach, these two numbers have no justification and are only used for demonstration), $V_{(D:T)} = 0.3$ (30% chance of being killed if hit by a rockfall), therefore $R_{(DI)} = 4.5 \times 10^{-4}$, higher than the acceptable value of 10^{-5} for average persons for existing slopes. For the egg-sized cinder falls, we have: $P_{(H)}$ = 20 (20 cinder rockfalls per year along the entire 500 feet long rock cliff), $P_{(S:H)}$ = 1/500*0.2*100% (each cinder fall only impacts 1 feet of the 500 ft area, no bouncing on beach (the factor of 0.2), and there is 100% chance for a rockfall to reach the beach), $P_{(T:S)}$ = 3 * 2 /24 (there are 3 persons for 2 hours each day on the beach at Black Sand Beach, again these two numbers have no justification and are only used for demonstration), $V_{(D:T)}$ = 0.1 (10% chance of being killed if hit by a rockfall), therefore $R_{(DI)}$ = 2 x10^{-4}, higher than the acceptable value of 10^{-5} for average persons for existing slopes. The total risk level would be 4.5 x10^{-4} + 2 x10^{-4} = 6.5 x10^{-4}.

Reference Cited:

Australian Geomechanics Society. 2000. *Landslide Risk Management Concepts and Guidelines*. Sub-committee on Landslide Risk Management. March.

Photo 1. Sources of rockfalls, indicated by S in the photo, on the rock cliff at Black Sand Beach, Makena State Park.

Photo 2. Sources of rockfalls, indicated by S in the photo, on the rock cliff at Big Beach, Makena State Park.

Photo 3. Close view of rockfall sources close to S1 as shown in Photo 1, Black Sand Beach, Makena State Park.

Photo 4. Close view of rockfall sources S2, S3, and S4 as shown in Photo 1. The arrows point to unstable loose cinder blocks perched on steep slope. Black Sand Beach, Makena State Park.

Photo 5. Close view of rockfall source S5 as shown in Photo 1 and rockfall debris piles (indicated by D) on the beach. Notice the vertical tension fracture (along the dashed line and pointed by the arrow). Black Sand Beach, Makena State Park.

Photo 6. Close view of rockfall debris pile D1 as shown in Photo 1 and Photo 5. Notice wave erosion has removed most of the debris. Black Sand Beach, Makena State Park.

Photo 7. Close view of rockfall sources S6 and S7 as shown in Photo 1. The arrows point to unstable loose cinder blocks. Black Sand Beach, Makena State Park.

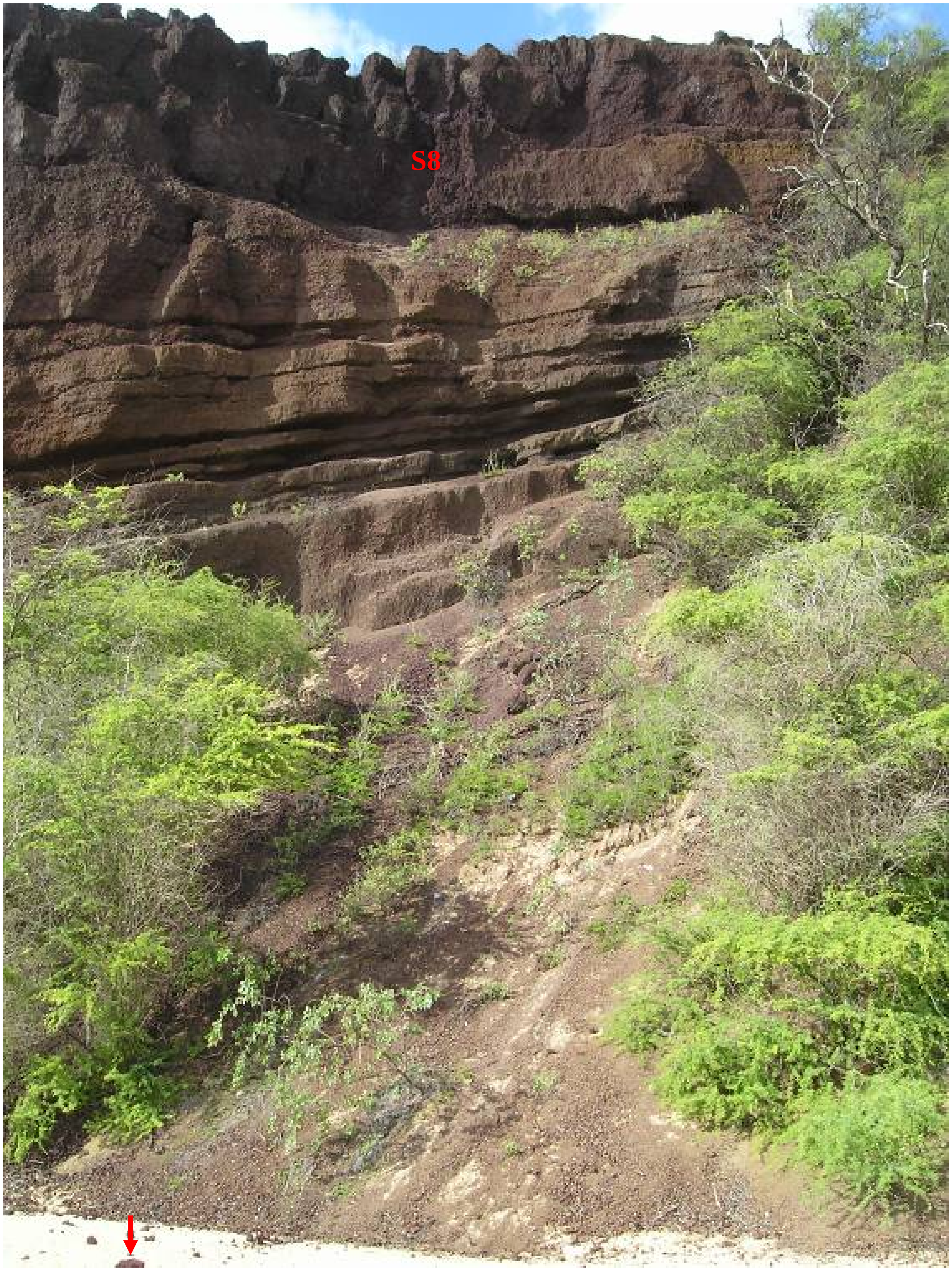

Photo 8. Close view of rockfall source S8 as shown in Photo 2. The arrow at left bottom of photo points to a rockfall debris on the white sand beach. Big Beach, Makena State Park.

Photo 9. Close view of rockfall source S9 as shown in Photo 2. The arrows point to unstable loose cinder blocks perched on steep slope. Notice S9 is a steep-dipping veneer cinder layer covering the gentle-dipping cinder layers shown in Photo 8. Big Beach, Makena State Park.

Photo 10. Rockfall debris of large cinder blocks (indicated by the arrow) at Black Sand Beach, Makena State Park.

Photo 11. Fallen boulders from the near vertical cliff stopped close to the cliff. Big Beach, Makena State Park.

Photo 12. Loose cinder blocks (indicated by the arrow) perched on the steep slope at Black sand Beach, Makena State Park.

Photo 13. Hard cinder layers (pointed by the arrows) develop significant overhand and tension fractures due to the differential erosion of soft layers underneath. Black Sand Beach, Makena State Park.

Photo 14. Detail of Photo 13 showing hard cinder layers sitting on top of soft cinder layers with well-developed tension fractures. Black Sand Beach, Makena State Park.

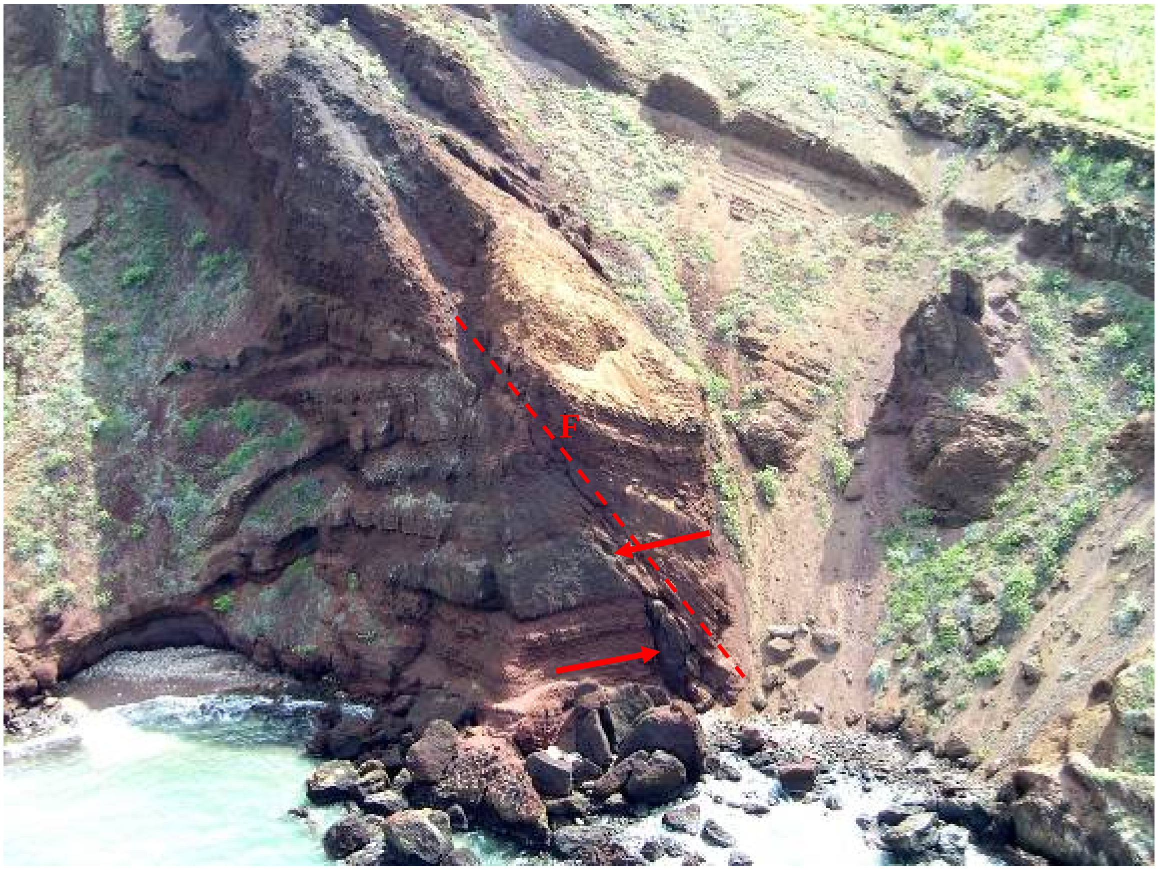

Photo 15. A fault zone (indicated by the dashed line). The two arrows indicate the dislocation of one cinder layer; the dislocation along the fault zone is larger. Black Sand Beach, Makena State Park.


Photo 16. Very loose cinder layers with poor cementation. Black Sand Beach, Makena State Park.

Photo 17. As most cinder layers at Black Sand Beach are very loose with poor cementation, falling of egg-sized (or larger) cinders onto the beach will be a constant problem. Black Sand Beach, Makena State Park.

Photo 18. Very hard cinder layers with strong welding at Big Beach, Makena State Park.

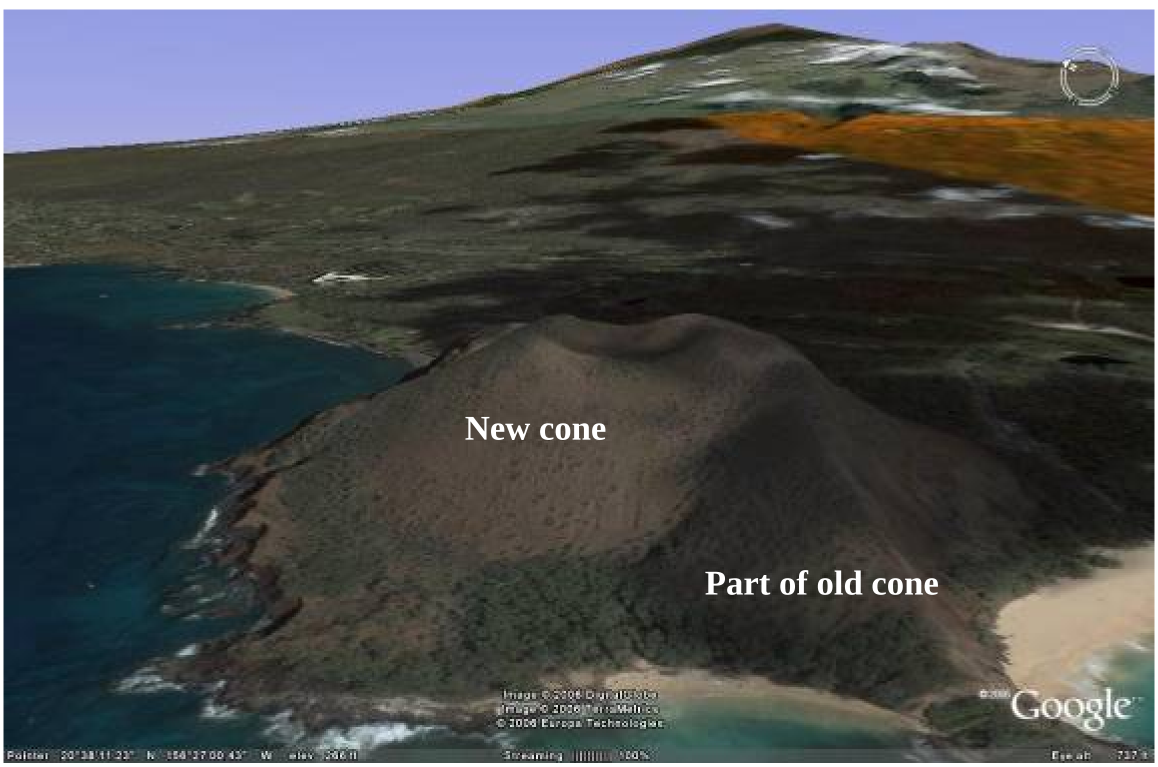

Photo 19. The new and old cones at Makena State Park.


Photo 20. A large fracture in the hard cinder layers atBig Beach, Makena State Park.